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Citation
Maoz, Dan, and Abraham Loeb. 2017. "Searching for Giga-Jansky Fast Radio Bursts from the Milky Way with a Global Array of Low-Cost Radio Receivers." Monthly Notices of the Royal Astronomical Society 467 (4) (February 17): 3920–3923. doi:10.1093/mnras/stx400.

Published Version
doi:10.1093/mnras/stx400

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Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 18 January 2017 (MN LaTeX style file v2.2)

Searching for giga-Jansky fast radio bursts from the Milky Way with a global array of low-cost radio receivers

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arXiv:1701.01475v2 [astro-ph.IM] 17 Jan 2017

18 January 2017

ABSTRACT

If fast radio bursts (FRBs) originate from galaxies at cosmological distances, then their all-sky rate implies that the Milky Way may host an FRB on average once every 30–1500 years. If many FRBs persistently repeat for decades or for centuries, a local giant FRB could even be active now. A typical Galactic FRB would produce a millisecond broad-band radio pulse with 1 GHz flux density of $\sim 3 \times 10^{10}$ Jy, comparable to the radio flux levels and frequencies detectable by cellular communication devices (cell phones, Wi-Fi, GPS). We propose to search for Galactic FRBs using a global array of low-cost radio receivers. Fainter FRBs could also potentially be detected, enabling a direct measurement of the FRB luminosity function. One possibility is to use the ~ 1 GHz communication channel in cellular phones through a Citizens-Science downloadable application. Participating phones would continuously listen for and record candidate FRBs (along with a foreground of artificial and natural noise sources) and would periodically upload information to a central data processing website, which correlates the incoming data from all participants, to identify the signature of a real, globe-encompassing, FRB from an astronomical distance. Triangulation of the GPS-based pulse arrival times reported from different Earth locations will provide the FRB sky position, potentially to arcsecond accuracy. Pulse arrival times versus frequency, either from reports from phones operating at diverse frequencies, or from fast signal de-dispersion by the application, will yield the dispersion measure (DM) which, when compared to a Galactic DM model, will indicate the FRB source distance within the Galaxy. A variant of this approach would be to use the built-in ~ 100 MHz FM-radio receivers present in cell phones for an FRB search at lower frequencies. Alternatively (perhaps optimally), numerous "software-defined radio" (SDR) devices, costing ∼$10 US each, could be deployed and plugged into USB ports of personal computers around the world (particularly in radio-quiet regions) to establish the global network of receivers.

Key words: stars: radio continuum, variables

1 INTRODUCTION

The origin and nature of fast radio bursts (FRBs) have remained enigmatic since the first FRB discovery by Lorimer et al. (2007). The 17 or so distinct FRB sources that have been reported so far are bright (~ 0.1–1 Jy) and brief (~ 1 ms) pulses of ~ 1 GHz radio emission (Lorimer et al. 2007; Keane et al. 2012; Thornton et al. 2013; Spitler et al. 2014; Burke-Spolaor & Bannister 2014; Petroff et al. 2015a; Ravi et al. 2015; Champion et al. 2016; Masui et al. 2015; Keane 2016). The pulse arrival times of FRBs show a ν^{-2} frequency dependence indicative of a passage through a cold plasma, with the so-called dispersion measure (DM) measuring the line-of-sight column density of free electrons. FRBs are selected to have large measured DMs of $\sim 300-1600$ pc cm^{-3}, in excess of the values expected from models of the interstellar electron distribution in the Milky Way galaxy, and have therefore been inferred to originate from extragalactic sources at cosmological distances. The cosmological distance has been confirmed in the case of the sole repeating FRB 121102, which has been localised to a dwarf galaxy at redshift $z = 0.19$ (Chatterjee et al. 2017; Tendulkar et al. 2017; Marcote et al. 2017).

The range of excess (above Galactic) DMs of the known FRBs correspond to a range of co-moving distances of 0.9–4.4 Gpc, with a median of 2.4 Gpc (corresponding to a redshift of $z = 0.64$), under the assumption that

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most of the excess DM is contributed by the intergalactic medium and using the standard cosmological parameters (Planck Collaboration et al. 2016). The latest estimate of the all-sky rate of FRBs with flux > 0.3 Jy is $1.1^{+3.8}_{-1.0} \times 10^4$ day^{-1} at 95% confidence (Scholz et al. 2016). This estimate is based on the single detection of FRB 121102, and ignoring the fact that it has been detected repeatedly over a period of 4 years. If FRBs occur in Milky-Way-like galaxies, we can divide the observed cosmological rate by the number of galaxies within the FRB survey volume, to find the expected FRB rate within a single such galaxy. We note that the recently localised FRB 121102 comes from an extreme-emission-line dwarf galaxy (Tendulkar et al. 2017), quite unlike the Milky Way. However, this host galaxy is not necessarily representative of all FRB hosts. The product between the comoving number density of L_* galaxies, $\sim 10^{-2}$ Mpc^{-3} (Montero-Dorta & Prada 2009), and the cosmological volume out to the median distance of known FRBs, 57 comoving Gpc^3, implies that an FRB should occur in our galaxy once per 140^{+1400}_{-110} years. A 0.3 Jy FRB from a comoving distance of 2.4 Gpc (a luminosity distance of 3.9 Gpc), placed at a typical Galactic distance of $\sim$ 10 kpc, would have an observed 1 GHz flux density of $f_\nu \approx 3 \times 10^{10}$ Jy or, equivalently, 3×10^{-16} W m^{-2}Hz^{-1}. FRB 121102 has been bursting repeatedly for at least 4 years. If most FRBs persist for decades or even centuries, a Galactic FRB could be active now. A powerful local FRB may have already been detected in the far side-lobes of radio telescope beams, but mistakenly ascribed to artificial interference.

Indeed, the radio flux density level of the received GHz-band signals from commercial radio stations, cellular communications and wireless networks is within a few orders of magnitude of the expected flux level from a Galactic FRB. For example, a typical desktop Wi-Fi transmitter operating at 2.4 GHz under the 802.11b standard has a radiated power of 100 mW over an 82 MHz bandpass with an outdoor range of $\sim$ 100 m, corresponding to a detected flux density of $f_\nu = 1 \times 10^{-14}$ W m^{-2}Hz^{-1}. Each of the transmitter's individual channels has a bandpass of 22 MHz, and therefore a time resolution of $\Delta t \sim 2 \times 10^{-8}$ s. By binning an incoming signal into millisecond ($\Delta t = 10^{-3}$ s) time bins a Wi-Fi receiver would improve its sensitivity in proportion to $\sqrt{\Delta t}$, i.e. by a factor of ~ 200, to a level of $f_\nu \sim 5 \times 10^{-17}$ W m^{-2}Hz^{-1} (5×10^9 Jy, i.e. 5 GJy). This is a factor 6 fainter than the typical Galactic FRB flux discussed above, and means that such a Galactic FRB, and even fainter and perhaps-more-frequent FRBs, would be detectable by existing communication devices. In the subsequent sections, we outline how an array of numerous low-cost radio receivers can be used to detect and localise giant Galactic FRBs.

2 A GLOBAL ARRAY OF CELLULAR RECEIVERS FOR GALACTIC FRB DETECTION

We consider below three related technical approaches to the assembly of an array of low-cost radio receivers, suitable for the detection of Galactic FRBs. The choice of the most practical approach will depend on several issues that need to be resolved, such as the ability to access and manipulate raw radio signals picked up by the antennas, the flux from FRBs at sub-GHz frequencies, the level of terrestrial noise at different locations, and the ability to filter out that foreground noise.

2.1 A cell phone communications channel approach

There are currently an estimated 7 billion active cellular phone accounts on our planet (similar to the number of people), operating in several frequency bands, from 0.8 to 2.4 GHz. Each of these phones is, as argued above, a radio receiver that is in principle sensitive to a Galactic FRB signal. Furthermore, every smartphone is a programmable computer capable of analyzing the signal, of timing it up to $\Delta t \sim 10^{-7}$ s precision with its global-positioning system (GPS) module, of storing this information, and of diffusing it through the internet.

We propose therefore to build a Citizens-Science project in which participants voluntarily download onto their phones an application that runs in the background some or all of the time, monitoring the phone's antenna input for candidate broad-band millisecond-timescale pulses that appear similar to an FRB. The application would record candidate FRB pulses (most of which originate from artificial and natural noise sources) and would periodically upload the candidate pulse information (pulse profile, GPS-based arrival time), along with information about the phone (GPS-based location, operating frequency) to a central processing website. The central website will continuously correlate the incoming information from all participants, to identify the signature of a real, globe-encompassing, FRB.

Because of the received signal's integration into ms time bins (required to improve the sensitivity to FRB levels, see above), every phone's actual arrival time accuracy will be no better than 10^{-3} s. However, improved time precision can be recovered by averaging the reported arrival times recorded by many participating phones at a similar location. For example, averaging the ms-precision reports from 10,000 phones within a city of radius 3 km (light travel time $< 10^{-5}$ s), would improve the precision by a factor of 100, to $\sim 10^{-5}$ s. Triangulation of the GPS-timed pulse arrival times from different Earth locations would then give the FRB sky position to an accuracy of order $\sim c\Delta t/2R_\oplus \sim 1$ arcmin. If time binning of the FRB signal, and subsequent loss of the native 10^{-7} s GPS timing precision could be avoided (a possibility considered in some of the other technical frameworks that we propose below), then naturally the localisation precision can be improved down to the sub-arcsecond level.

Because of the ν^{-2} arrival-time dependence of a radio pulse propagating through the Galactic plasma, phones operating at diverse frequencies (multiple networks and phone models) will receive the signal at a time delay,

$$\delta t = 0.144 \times \left(\frac{\mathrm{DM}}{200\ \mathrm{pc\ cm^{-3}}}\right)\left(\frac{\nu}{2.4\mathrm{GHz}}\right)^{-2}\ \mathrm{s}. \quad (1)$$

Over, e.g., a 22 MHz cellphone channel bandwidth at 2.4 GHz, a typical Galactic DM of 200 pc cm^{-3} (Rane & Loeb 2016) will spread the FRB arrival time over just 2.6 ms, comparable to typical FRB pulse widths. The channel bandwidth therefore will not result in any significant smearing of the pulse over time, which could have reduced the detection sensitivity and timing precision. By comparing the arrival times of different frequencies at the same locations, the central website will be able to solve for the FRB's DM that, when compared to a Galactic DM model (Cordes & Lazio 2002; Yao et al. 2016), will indicate the FRB source distance within the Galaxy. Alternatively, the application software itself could attempt to de-disperse all candidate incoming signals across the full frequency range available to each receiver. With efficient new algorithms, real-time de-dispersion of FRB signals is now feasible on small computers (Zackay & Ofek 2014; Zackay 2017), and so is likely possible on smartphones as well. In such a scenario, the identification of a ν^{-2} frequency sweep would be a real-time test of incoming signals, performed at the level of each individual receiver.

One clear advantage of the above operation plan is that it is essentially cost free—all of the necessary hardware (the world's cell phones) is already in place, and one needs only to carry out the plan's organizational steps in order to make it work for the scientific program. Potential problems with this proposed mode are, first, that cell phone may be hard-wired at the basic electronics level to demodulate and digitize incoming communications signals, and therefore the raw broad-band radio signal containing the FRB may be inaccessible to software. Furthermore, mobile phone communications are encoded so as to allow many users to share the frequency band, and this encoding permits the detection of communication signals at sub-noise levels (as opposed to the un-encoded FRB signal). The foreground of cellular and other communications emissions, or natural radio noise, may produce too much confusion for isolating the desired millisecond-timescale FRB signal. These questions require further study.

2.2 A cell phone FM radio channel approach

Most or all cell phones have built-in FM-band radio receivers operating at around $\nu \sim 100$ MHz and enabling direct (i.e. not through the internet or the service provider) reception of radio broadcasts. Interestingly, this hardware is de-activated by phone manufacturers in about $\sim \frac{2}{3}$ of all phones, in the service-providers' interest of having the customers download and pay for the radio broadcasts, rather than receiving them for free. Nevertheless, about $\frac{1}{3}$ of all phones (still a sizeable number when considering the global number) do have the direct FM reception option activated. The raw, non-demodulated radio signal from this channel is more likely to be accessible to the application software in its search for an FRB signal than in the preceeding approach using the ~ 1 GHz cellular communication channel. A shortcoming of this option, however, is the yet-unknown properties of FRBs at ~ 100 MHz frequencies. Current upper limits from FRB searches at 145 MHz (Karastergiou et al. 2015) and 139-170 MHz (Tingay et al. 2015), limit the FRB spectral slope to $> +0.1$. As with the ~ 1 GHz cellular-communications option, discussed above, here too integration over time could make a typical Galactic FRB detectable at 100 MHz, even for more positive slopes as high as $+1$, such that the FRB would have $\gtrsim 5$ GJy at 100 MHz. The foreground noise question in this option is similar (though in a different frequency band) to that in the previous, cellular-communications, option.

2.3 A software-defined radio approach

A software-defined radio (SDR) is a radio system where components such as filters, amplifiers, demodulators, etc., that are typically implemented in hardware, are implemented instead in software on a personal computer. SDR devices are widely available for $\sim$\$10 US a piece, and they are popular with radio amateurs. They are often the size of a memory stick and likewise can be USB plugged. An SDR device includes an antenna than can detect the full raw ambient radio emissions over some frequency range and can input them with minimal processing into a computer, where the signals can be software-processed at will. Our third approach is therefore to deploy a large number (depending on the available budget) of such SDR devices, to be plugged into participating personal computers around the globe, or base the network on devices already in use by participating radio amateurs. As with the phone option, the participants will download and install software that will continuously monitor the input from the SDR. As before, the computers will upload the information on candidate Milky Way FRBs to a central data-processing website.

A disadvantage of this approach is the need to actually buy and send the SDR hardware to the selected participating individuals of the network (unless one takes the existing-amateur-SDR approach). The advantages involve having an accessible FRB signal, uniformly processed and fully analysable at will (including spectral information from every station). Every SDR could be supplemented with a simple exterior antenna or antenna booster (wireless reception boosters are also widely and inexpensively available for cell phones and laptops) that would considerably enhance its sensitivity, lowering or fully avoiding the need for time integration, and hence for the sacrifice of timing precision, or simply probing for fainter and more frequent bursts (see below). Furthermore, the ability to choose the stations sites at will in a well-spaced global network, specifically in "radio-quiet" locations with minimal artificial and natural radio interference, may prove to be the most important benefit.

3 LOWER-FLUX, MORE-COMMON GALACTIC FRBS

A major practical problem of the schemes described above are the long and uncertain timescales—decades to many centuries—expected for the detection of a single, Galactic 3×10^{10} Jy FRB, unless typical FRBs persistently repeat for decades or centuries (which is a real possibility, given the case of FRB 121102). If FRBs typically do not repeat, then even for the more optimistic end of the rate estimate, broadcasting standards, phone models and other technical factors, may change over a decade, not to mention the limited patience of the participants and the experiment managers. A resolution of this concern, however, could be based on the fact that FRBs must have a distribution of luminosities. Indeed, if the known FRBs are at the cosmological distances indicated by their excess DMs, then they are clearly not "standard candles". A reasonable expectation is then that FRB numbers increase at decreasing luminosities. If so, lower-luminosity FRBs should be detected more frequently by the global cellular network.

Let us assume that we can parameterize the FRB number per unit luminosity with a Schechter form,

$$\frac{dN}{d(\log L_\nu)} \propto L_\nu^{-\alpha+1} e^{-L_\nu/L_{F\star}}, \qquad (2)$$

where $L_{F\star}$ corresponds to the characteristic specific luminosity of an FRB source (namely, the one that yields an observed flux density of ~ 0.3 Jy at a luminosity distance of ~ 4 Gpc). One way to calibrate α is by speculating that the Galactic population of rotating radio transients (RRATs; McLaughlin et al. (2006)), which have some properties in common with FRBs, constitute the low-luminosity counterparts of FRBs. The rate of RRATs over the entire sky, $\sim 10^6$ day^{-1}, is somewhat larger than that of "extragalactic" FRBs, and thus the RRAT rate is $\sim 10^{11}$ times the Galactic FRB rate. The typical RRAT flux of ~ 0.3 Jy corresponds to $\sim 10^{-11}$ the typical flux of a Galactic FRB. If these two populations of transient radio sorces are related, then $\alpha \approx 2$. Interestingly, this value corresponds to an equal luminosity contribution from transients per logarithmic interval of luminosity.

The flux distribution from a Galactic FRB population having a particular luminosity will be $(dN/d(\log f_\nu))|_{L_\nu} \propto f_\nu^{-3/2}$ for a spherically distributed population (e.g. in the Galactic halo), or $\propto f_\nu^{-1}$ for a planar distribution (e.g. the Galactic disk)— coincidentally matching the power-law scaling at low fluxes in the luminosity function for $\alpha = 2$. At a 5 GJy flux level, still detectable by our proposed arrays, one might then expect to find Galactic FRBs 6 times more frequently than at 30 GJy, i.e. once per 5 to 250 years. Increasing the sensitivity by one or two orders of magnitudes, e.g. by adding simple antennas in the SRD option, would potentially allow for the detection of Galactic FRBs on a yearly to weekly basis, and for the direct determination of their luminosity function.

4 CONCLUSIONS

We have shown that if FRBs originate from Milky-Way-like galaxies at cosmological distances, then their all-sky rate implies that the Galaxy hosts an FRB every 30 to 1500 years. If many FRBs repeat, and for long enough, then the occurrence frequency could be higher, and a local FRB may even be active now. A typical Galactic FRB will be a millisecond broad-band radio pulse with 1 GHz flux density of $\sim 3 \times 10^{10}$ Jy, not much different from the radio flux levels and frequencies detectable by cellular communication devices (cell phones, WiFi, GPS). Our proposed search for Galactic FRBs using a global array of low-cost (possibly already existing) radio receivers would enable triangulation of the GPS-timed pulse arrival times from different Earth locations, localising the FRB sky position to arcminute or even arcsecond precision. Pulse arrival times from devices operating at diverse frequencies, or from de-dispersion calculations on the devices themselves, will yield the DM that, when compared to a Galactic DM model, will indicate the FRB source distance within the Galaxy. Fainter FRBs could potentially be detected on a yearly or even weekly basis, enabling a direct measurement of the FRB luminosity function.

ACKNOWLEDGMENTS

We thank C. Carlsson, A. Fialkov, J. Guillochon, Z. Manchester, E. Ofek, M. Reid, and B. Zackay, for useful advice and comments. This work was supported in part by Grant 1829/12 of the I-CORE program of the PBC and the Israel Science Foundation (D.M.) and by a grant from the Breakthrough Prize Foundation (A.L.). A.L. acknowledges support from the Sackler Professorship by Special Appointment at Tel Aviv University.

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